Preliminary Estimates of Possibilities for Developing a Deployable Greenhouse for a Planetary Surface (Mars)

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Introduction

Mars is one of the planets nearest Earth in the Solar System. Climatic conditions on Mars somewhat resemble those of the polar regions of Earth, so this planet is a prospect for exploration in the near future. However, the long-term success of this exploration will depend on the possibilities of plant production on the Martian surface.

Work done to date, including the BIOS-3 Project of 1960 to 90 in Russia, EEC Project of 1960 to present, CELSS Program of 1960 to present in Russia, USA, Japan, and elsewhere, and the Biosphere-II project, can furnish data to estimate plant production capabilities for a Deployable Greenhouse (DG) on Mars.

Physical conditions on the Martian surface demand specialized facilities for sustaining the growth of terrestrial plants. The ambient atmospheric pressure is less than 1% of Earth's, with an average temperature near -57 °C to -60 °C. There are large daily (23 °C to 73 °C) and seasonal (-125 °C to 18 °C) thermal fluctuations. A Martian day is 1.027 X that of Earth's, while year on Mars is 1.88 of Earth's. Annual average insolation is approximately 0.43 of Earth's, or about 600 W m^{-2}, and changes in seasons of the Mars year are 1.45 times those of Earth. These conditions can cause dust and sand storms on the surface of Mars when wind speeds exceed ~100 m s^{-1}. The normal duration of such storms is 50-100 days. The height of a storm can exceed 7-15 km (5). Dust and sand from these storms could accumulate on a DG on Mars and reduce the light transmitted into DG if it is not removed.

Two of the main conditions for plant growth and development on the Martian surface are irradiation (optimal range from 80 W m^{-2} to 180 W m^{-2} of photosynthetically active radiation) and temperature (optimal range from 20 °C to 27 °C). The only known natural source of energy on Mars is sunlight, with a general intensity of 589 ± 142 W m^{-2} (Martian Solar Constant, calculated from data in 4, 5, and 6).

Comparisons of plant growth requirements with conditions on the Martian surface are presented in Table 1, while some basic considerations for implementing plant growth in a Martian DG are presented in Table 2. The general scenario and approximate schedule of startup and development of operations in the DG are shown in Table 3. Issues related to mechanical maintenance and repair of a DG on the Martian surface are not addressed in this paper.

Table 1. Growth conditions and demands for higher plants in a Martian surface greenhouse.

Parameter	Units	Low value	High value	Optimal value	Expected outside range [5]	Proposed actions to maintain plants in DG
Temperature	°C	+5.0	+35.0	+20 to + 27	-125 to -10	Additional heating, up to 500 W/m²
Atmospheric pressure	kPa	10.0 (?)	100	100	0.5 to 0.7	Stock of atmospheric gases
Photosynthetically active light (400-700 nm)	W/m²	50	500	150 to 200	0 to 277 (outside DG) 0 to 90 (inside DG)	Additional illumination up to 100 W/m² PAR
Partial pressure CO_2	kPa	0.03	3.0 to 5.0	0.1 to 0.2	0.5; 95% of vol. of atmosphere	Artificial composition of atmosphere with low pressure
Partial pressure O_2	kPa	5.0	27 to 30	10 (?) to 22	Trace levels	
Relative Humidity	%	55	100	70 to 85	~0.1 % of vol. of atmosphere	Rapid water recycling in low atmospheric pressure

Table 2. Problems of implementing a plant production system in closed, unmanned volumes.

Problem	Initial Approach to a Solution	Source of Data for the Approach	Comments	Nearest experimental works
1. CO_2-supplying, -O_2-removal & accumulation.	1A. Burning of carbon stock (biomass, packaging) 1B. Injection of CO_2-enriched from storage, with simultaneous extraction of O_2-enriched air for storage.	BIOS-3 experiments (IBP data) BIOSPHERE - II NASA's CELSS program and other.	The system of O_2 accumulation will increase the weight of the DG Probability of successful realization p_1=1.	Growth of plants in atmospheres of low pressure and modified composition.
2. Provision and maintenance of plant nutrients.	2A. Use of nutrient-enriched, synthetic soil for plant growth 2B. Continual monitoring and correction of pH and nutrient levels in solutions.	Greenhouse SVET (IBMP- Moscow) BIOS-3, NASA CELSS, Biosphere-II, KARUSEL (at IBP -Krasnoyarsk), Others.	The weight of the DG is practically the same in both variants. Probability of successful realization p_2 = 1.	Restoring and continuing work on supplying plants with liquid nutrients in low gravity conditions.

3. Heat exchange.	Using special engineering constructions (e.g., double layer extrusion from synthetic materials) and configuration.	Experience of heat removal from space stations. Experiments needed to determine thermal conductivity and transfer of simulated Martian soils.	Any additional installations make the DG heavier. Probability of successful realization $p_3=1$	Experiments with small scale DG-model to evaluate heat exchange in conditions similar to Martian surface. Selecting DG materials and developing configurations.
4. Dust removal from DG and additional illumination.	4A. Removal of dust by automated, mechanical systems 4B. Installation of lighting system.	Experience from BIOSPHERE-II, BIOS-3, and others. Additional experiments in rarefied atmospheres are needed.	Installation of dust-removal systems for increases the weight of DG. It is possible that natural processes (e.g. wind) will limit or control dust accumulation. Probability of successful realization $p_4=1$	Experiments with small scale DG-models to evaluate dust accumulation mechanisms and related conditions of illumination. These to be combined with heat exchange experiments.
5. Spectral composition of light.	Combination of natural light, transmitted through transparent material, and artificial light of special spectral composition.	Greenhouse SVET, BIOS-3, NASA-CELSS. Experiments with the transparent materials for DG are needed.	Additional lighting. Probability of successful realization $p_5=1$. These estimates need evaluation by materials specialists.	Selection of materials to reduce the UV radiation.
6. Managing the chemistry of the transpired water and water recycling.	Develop on Earth the requirements for the stock of correcting salts and reagents.	BIOS-3 long-term experiments, NASA CELSS, and others.	This problem will appear when people arrive at the DG on Mars. Probability of successful realization $p_6=1$.	Humidity experiments in combination with heat exchange experiments.
7.Contamination by microbial & organic materials (may develop during long-term operations).	Catalytic thermal oxidation of microbial & organic contaminants in air.	BIOS-3 long-term experiments & the BIOSPHERE-II 2-year experiment. Additional long-term experiments are needed.	Oxidizing microbial & organic contaminants may produce oxides that are toxic for plants. Thermal oxidizing equipment will increase weight of DG. Probability of successful realization $p_7=0.9$.	Long-term experiments with microbial composition of closed environments containing higher plants.
8. Unknown factors: Influence of low gravity, high level of space radiation, etc.	Experiments with higher plants in MIR and Intl. Space Station.	Data about higher plant growth in space station MIR (NASA & Institute of Biomedical Problems, Moscow).	$p_8=?$	Experiments with higher plants in conditions approaching that of Mars (Intl. Space Station and MIR)

Table 3. Possible scenario for deploying an inflatable greenhouse on a planetary surface.

Name of Phase	Approximate Time of Development, Days
1 Arrival, installation and inflation on the surface of the planet: installation of supplemental lighting, start of the water cycle, supply of nutrients and CO_2, installation of additional lighting and heating, etc.	0.3 to 7 d; depends on DG sizes and level of technical development.
2. Initiation of plant growth: planting and cultivation of different crops, accumulation and extraction of O_2, adjustment of nutrient solutions.	~ 90 d; depends on the time of development of the slowest crop.
3. Arrival of personnel: initiation of closed cycle air exchange, nutrient supply, and water recycling; and of harvesting, processing and transportation of solid plant matter, etc.	Up to 180 d for steady-state operations. Confirmed by direct experiments in BIOS-3

The duration of the first stage of deployment is determined by engineering and technical considerations, and could be up to one week. The duration of the second stage is determined by biological considerations, especially the development time of the slowest crop. Faster-growing crops might be started later to synchronize finish times for crew arrival. Alternatively, early maturing crops may have to be maintained in an air-dry state while other crops grow to maturity. The last stage's duration depends on the overall goals and schedules of the Mars mission.

All the following calculations and estimates are based on a 3-member crew, mainly because:

A. Standard crew for an DG should include at least a technical engineer, a biologist-agronomist, and a medical specialist.
B. For the BIOS-3 project, all experiments were conducted with a 3-person crew, so the data from that work may be applied directly, without recalculation.
C. It is easy to manage an DG of such dimensions.
D. An DG functions as one entity, with one stock of substances and one system of controls. The 3-person DG can be duplicated if numbers of participants increase.

Experiments with the BIOS-3 System showed that for supplying three persons with oxygen, water, and the vegetable part of their diets (35% to 45%), lighting of 120 to 150 W m^{-2} PAR was adequate on 94.5 m^2 (where 41.0 m^2 was for plant growth, 31.5 m^2 was for habitation, and the remainder was walkways). Volume of the BIOS-3 facility used for these tests was 244.25 m^3, with an unused volume of 78.75 m^3 and area of 31.5 m^2 available for emergency / contingency.

Initial approaches to solving problems of Martian DG implementation

1. CO_2 supplying – O_2 removal and accumulation

Maintenance of the composition of the atmosphere for automatic plant cultivation can be provided by at least two modes (Table 2).

1A. Burning of the waste carbon, for example dry cellulose. It can easily be operated automatically. According to the experiments with the BOIS-3 System [2, 3] the dry weight of plant products which supply a 3-person crew by vegetarian diet, water and oxygen are about 173 kg. 70-80% of this weight is polysaccharides. So, the initial stock of cellulose for the DG is

about 130 kg. 43 kg is the stock of mineral salts for nutrient solutions. A consequence of burning waste carbon would be the consumption of O_2.

If it is proposed to maintain plant cultivation after the initial plant conveyor is established, the stock of cellulose must be increased. In any case the probability of realization of this element of DG development can be estimated as $p_1=1$.

1B. Technically it is easy to inject air enriched in CO_2 or CO_2 from the Martian atmosphere, while simultaneously extracting and storing O_2-enriched air. In principle, it is possible to estimate the probability of this as $p_1=1$. Experiments are needed to determine how often the enriched CO_2 atmosphere must be injected into the DG, and what degree of enrichment is optimal. This approach obviously increases the weight of the system by the addition of containers and pumps. In any case, when the crew arrives, they become the main source of CO_2 for the plants.

2. Correction of nutrient solutions

There are extensive data from calculations and operations of plant production facilities on the use nutrient solutions for plant cultivation in controlled environments [2, 3]. The question is how to automatically and remotely manage these solutions. Two possible approaches are:

2A. Use of a synthetic soil substrate for plant growth, enriched by biogenic solutions. Numerous data are accumulated in the Institute of Biomedical Problems (IBMP, Moscow) and in the framework of NASA's CELSS program. So, the probability of realizing this approach can be estimated as $p_2=1$.

2B. Continual monitoring and correction of pH and nutrients levels in solutions [2, 3]. There are numerous data in this area from the BIOS-3 project (IBP, Krasnoyarsk) and in from CELSS program experiments. When we know the average plant productivity and biomass composition through growth and development, it is possible to calculate frequency and quantity of additions/corrections to nutrient solutions. The correction of pH could be made automatically with a pH-meter. Because these operations would be similar to those on Earth ,the probability of success could be estimated as $p_2=1$.

3. Heat exchange

Mars receives an average of 600 W m^{-2} of solar radiation [4, 5, 6]. During a dust storm, perhaps 30% of this reaches the surface of the planet, and during a clear time about 70%. Thus the atmosphere can attenuate 170 to 400 W m^{-2}, depending on conditions. In the DG, almost all of the remaining incident radiation will convert to heat because the relatively low photosynthetic conversion efficiency (e.g., up to 5.0% - 8.0% converted to biomass). Heat removal to the Martian atmosphere is difficult because it is less than 1/100 the density of Earth's atmosphere. Thus the DG will gain heat by solar radiation, any supplemental heat, and waste heat from any supplemental lighting system.

Heat transfer from objects inside DG will involve conduction through the air mass to the walls, convection within the air mass, and radiant heat exchange between objects inside and the wall material. Depending on the temperature of the walls, latent heat exchange involving evaporation and condensation of water on the wall surfaces will also occur.

Synthetic materials can be treated or coated to block infrared in the same way that glass does, but they still might be thin with low thermal resistance, so the wall materials will reach equilibrium with the outside environment. Here, conduction heat transfer between the outside wall surface and the outside environment should be minor, and convection heat transfer to the atmosphere should be minor, except when air velocities do reach rates of near 100 m s^{-1}.

The outside surfaces of DG will exchange radiant heat with the sky and with all objects in their field of view. The rate of this transfer will depend on the emissivities, absorptivities and

temperatures of the outside wall surfaces, the surrounding objects, and the sky temperature. The temperatures of the outside and inside wall surfaces will be close to equal if the thermal resistance of the wall material is low. If the thermal resistance of the wall material is high, then the inside wall temperature will approach the inside air temperature, and the outside wall surface temperature will reach some value in equilibrium with the outside overall thermal environment.

A rough estimate of the thermal range in the Martian DG can be made from the equation:

$$\dot{T}=\left\{\frac{\left(\frac{1}{k_R}-1\right)\left(k_T J_o+I_o\right)}{\left(\frac{1}{k_R}-1\right)+k_T}+H-\frac{k'_T}{k'_R}\cdot\frac{\sigma T^4}{\left(\frac{1}{k'_R}-1\right)+k'_T}-\frac{k_S+\varphi k_A}{\ell}\left(T-T_o\right)\right\}\frac{G}{cm};$$

where:

k_R=coefficient of reflection of light from inside of DG ($0 < k_R < 1$);

k_T=coefficient of transmittance of light inside of DG ($0 < k_T < 1$);

k'_R=coefficient of reflection of long-wave's infrared radiation from inside of DG ($0 < k'_R < 1$);

k'_T=coefficient of transmittance of long-wave's infrared radiation outside of DG ($0 < k'_T < 1$);

k_S=coefficient of thermal conductivity of DG's material into Martian soil;

k_A=coefficient of thermal conductivity of DG's material to the Martian atmosphere;

G =area of light absorbing surface (floor) of DG;

c =heat capacity of the Greenhouse (includes capacities of water, plants, walls, etc);

m =average prearranged mass of DG;

ℓ =thickness of the material of DG;

J_o=the intensity of outside source of light (Martian Solar Constant);

I_o= the intensity of inside source of light;

H = the intensity of additional inside the DG heating;

T_o=average temperature outside the DG;

T =average temperature inside the DG;

φ =DG shape geometrical coefficient (ratio, of the area of surface that is contacting the Martian atmosphere, to the area of the floor);

σ=Stafan-Boltsmann constant, for radiation of absolutely black body.

If heat conductivity of the atmosphere is not high, and the deviation of inside DG temperature from outside temperature is not large, it is possible to use this next approximation:

$$\Delta\dot{T}=\left\{\frac{\left(\frac{1}{k_R}-1\right)\left(k_T J_o+I_o\right)}{\left(\frac{1}{k_R}-1\right)+k_T}+H-\frac{k'_T}{k'_R}\cdot\frac{\sigma T_o^4}{\left(\frac{1}{k'_R}-1\right)+k'_T}\left[1+4\frac{\Delta T}{T_o}\right]-\frac{k_S}{\ell}\Delta T\right\}\frac{G}{c}$$

where: $\Delta T = T - T_o$

By using this approximation, it is possible to get some estimates of the temperature ranges in DG related to outside temperatures, and of the additional actions that would be needed to maintain optimal temperatures for growth of terrestrial plants. The correct values of some significant coefficients are unknown at this time. So, we need to make reasonable assumptions concerning them:

k_R=0.25 (assumed on the basis of data from [1, 4];

k_T=0.93 (assumed and calculated on the basis of data from [1, 4];

k'_R=0.05 (assumed on the basis of data from [1, 4, 6];

k'_T=0.8 (assumed on the basis of data from [1, 4, 6];

k_S=2.1 W$\cdot$ cm/m^2 $\cdot$grad (assumed on the basis of data from [4];

ℓ~1.0 cm (assumption);

σ=5.67 $\cdot 10^{-8}$ W/m$^2\cdot$ grad^4 (value from [4, 6]; calculation)

J_0=589 W/m^2 (calculation on the basis of data from [4, 5, 6].

The results of these calculations are presented in Table 4.

Table 4. Estimates of temperatures in DG on Martian surface, and additional actions needed to maintain the optimal range

Different times of Martian day and year	Temperature (°C)		Additional actions to maintain the optimal range of temperatures (calculations)
	Martian surface [5]	DG without additional actions (calculations)	
1. The end of night and early morning.	-73	-73	Additional illumination or heating up to 600 W/m^2.
2. About noon	-23	+24.4	There are no additional actions.
3. Evening and early night.	-45	-42.3	Additional illumination or heating up to 300 W/m^2.
4. Winter (about noon)	-125	-14.0	Additional illumination or heating up to 100 W/m^2.
5. Summer (about noon)	-18	+26.1	There are no additional actions.

For more precise estimations, we need in more accurate data about round-the-clock and round-the-year values of the basic parameters of the Martian environment at different latitudes. In addition, more accurate values are needed for the coefficients in the mathematical models. These values could be found from experiments with small scale physical DG models in conditions approaching the Martian environment (low temperatures and pressures in an atmosphere containing 97% CO_2 , with sand and dust depositing on surfaces, etc.). The basic elements of plant growth implementation in the Mars DG are presented in Table 2. The general scenario and schedule of the startup and development of operations in the DG are in Table 3. I have not considered problems of mechanical maintenance and repair of the DG on the Martian

surface for this discussion because it is not directly connected with plant growth, but clearly these are important issues.

4. Dust accumulation and conditions of illumination

The intensity of illumination in DG can be calculated according to the formula:

$$I = k_1 \cdot k_2 \cdot k_3 \cdot k_4 \cdot I_o ,$$

Where Io - intensity of illumination on the Earth (Solar Constant);

k1 - decrease caused by greater distance from Sun, than Earth;

k2 - decrease in the atmosphere of Mars;

k3 - decrease by dust accumulated on the surface of DG;

k4 - decrease in passing through the transparent material of DG.

If Io = 1.37 kW m^{-2} [4, 5, 6];

k1 = 0.43 [5];

k2 = 0.30 (in the dust storm); = 0.71 (in the clear sky) [5, 6];

k3 = 0.3 to 0.5 (currently unknown; assumption);

k4 = 0.33 to 0.53 (currently unknown; assumption and calculation from [1]).

So, the range of insolation in DG could be:

$$I = (0.047 \text{ to } 0.194) \text{ kW m}^{-2}$$

Photosynthetically active radiation (PAR) is approximately 47% to the total solar spectrum. That is I of PAR would be ~0.022 to 0.091 kW m^{-2}. The low value is less than the PAR compensation point for photosynthesis of some plants, while the higher value is acceptable for photosynthetic productivity, but lower than optimal. Accordingly, in this situation, it is probably better to have the capability for additional illumination in the DG for optimal plant growth and development. This estimate is based on a narrow band of equatorial Martian latitudes, and in the part of the Martian orbit which is nearest the Sun. But it is well known that the orbit of Mars is very elliptical. Alternatively, a special installation for dust and sand removal from DG surface would be needed. This would increase the intensity of PAR entering DG by a factor of 2 or 3. In addition, about 8% of the UV (ultraviolet light) needs to be filtered out [6] to protect terrestrial plants. The probability of successful realization p_4=1.

5. Spectral composition of light

Spectral composition of the solar light on Mars is important, particularly the portion of UV (ultraviolet). The intensity of incident UV must be reduced, which is probably not technically difficult. Light transmittance testing of transparent materials for the DG is needed. The IR (infra red) needs to be absorbed by DG. So, the probability of realization of this element of plant growth is p_5=1, because it depends on the selection of materials for DG. This evaluation should be done in more detail by group of specialists.

6. Management of the chemistry of transpired water

This problem becomes important when people arrive at the DG on Mars. Experiments with the BIOS-3 System, for example, showed that after some additional cleaning and mineralization, transpired water can be used for drinking, for sanitation and other uses, after the usual boiling [2, 3]. Numerous measurements showed that 1 m^2 of illuminated plant gives 6.2 to 7.1 L day^{-1} of condensed water. So the needs of one person could be satisfied with at little as 2 to 3 m^2 occupied by higher plants [1,2].

Thus, the initial stock of water for DG for 3 persons can be estimated as follows: water, circulating between plants in the phytotrons - 100 to 200 kg (according to BIOS-3 data); water, accumulated in the biomass of the plant system - 164.4 kg (according to BIOS-3 experimental data); evaporated water (at an operating temperature of 20°C) not more than 6.9 kg (according to ref. 3 and BIOS-3 data). Therefore, the whole stock of water would 271.3 to 371.3 kg. Probability of realizing water cycle can be estimated as $p_6 = 1$, based on the successful experiments in BIOS-3, the CELSS-program, and Biosphere-II. Calculations from a simple mathematical models shows that humidity in a Martian DG with the same dimensions as BIOS-3 could be about 75%.

6. Contamination by microbial and organic materials

Experiments with the BIOS-3 system showed that microbial growth did not reach steady-state conditions in quality and quantity during 180 days of continuous operations (1, 2). There were no dangerous microbial influences on the plants during that period. However, such contamination could be a problem for longer-term operations as in the Mars mission, and in general, it may be among the more troublesome technical areas for the long-term success of the project.

In any case, in a characteristic period of up to 90 days (the time for development of plant production in the DG) the probability of realization of acceptable conditions for plant growth in this item can be estimated as $p_7 = 0.9$, because the problem only appears in long-term operations. Duration of the Mars mission is about $t \approx 2$ years. Based on successful experimental operations with BIOS-3, in the microbial organic contamination time might be estimated at $T \sim 20$ years. So p_7 can be estimated according formula $p_7 = 1 - t/T \approx 0.9$.

7. Unknown factors

There could be long-term influences from low gravity on higher terrestrial plants, from high levels of space radiation, or from other unanticipated factors. So, it is difficult to estimate the probability for p_8. Thus is it important to continue the experimental program with higher plants with MIR and the International Space Station.

Conclusions

The general probability of successful realization of the DG project based on this data can be evaluated as:

$$P = p_1 \cdot p_2 \cdot p_3 \cdot p_4 \cdot p_5 \cdot p_6 \cdot p_7 \cdot p_8 = 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 1.0 \cdot 0.9 \cdot ? \approx 0.9 \text{ (neglecting } p_8 = ?)$$

Thus an uncertainty of 0.1 must be eliminated by experiments within the 3-year period of preparation of the DG Project for the Mars mission.

A preliminary list of experiments to prepare for the DG is presented in Table 2 (last column), and a preliminary evaluation of the minimum weights of the biological part of DG is presented in Table 5.

Clearly there are lingering uncertainties. For example, the probability of success may be lower than estimated; e.g., $p_8 \cdot p \rightarrow 0$. Hopefully the planned 3-year program of work under conditions similar to those of Mars will reduce these uncertainties.

For better estimates, and for further development of DG project, the following is needed:

1. Detailed data on the ranges of the Martian surface climatic and environmental parameters (round-the-year and round-the-clock values of insolation, temperatures, heat exchange, wind velocity, atmospheric density, etc).
2. More precise mathematical models, describing:
   day-to-night environmental changes of the planet surface,
   heat exchange between DG and the thermal environment of Martian surface,
   and possibly other factors.
3. Designing DG configurations according to optimize the ratio of wall area to contained volume (low values assist in retaining heat, while higher values can provide better lighting).
4. Selecting and developing DG cladding materials that afford a high level of natural illumination and heat conservation at the same time (e.g., double layer extrusion).
5. High thermal resistance of wall material to prevent condensation or freezing of evaporated water on inside surface of the DG walls.

Table 5. Minimum initial mass of materials for development of a plant production system based on BIOS-3 experiences (for 3 persons).

Main components	Mass	Comments
1. Seeds and other materials for planting	39 kg	High mass is caused by chufa and potato. If seeds only are used, weight can be reduced.
2. Biomass/cellulose for burning	130 kg	---
3. Stock of nutrient salts	43 kg	---
4. Synthetic soil substrate and material for mechanically maintaining plants upright	About 2000 kg	If expanded clay aggregates are used. If synthetic materials are used, mass could be reduced.
5. Initial water	270 - 370 kg	---
6. Initial atmosphere (dry air)	About 394 kg	If DG is operated at lower pressure, this could be reduced.
Total weight	2876 to 2976 kg	Could be decreased by using synthetic materials and by implementing a DG project with reduced atmospheric pressure and/or modified composition.

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